INVITED

Paddock-scale Models and Catchment-scale Problems : The role for APSIM in the Liverpool Plains.

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Abstract Agricultural systems are managed at the paddock scale and yet their net impacts are often not confined to the unit of management. Dryland salinity in the Liverpool Plains is an example of a catchment scale problem that results, at least in part, from the individual decisions made by land managers at the paddock scale. This paper considers the place for paddock-scale simulation of agricultural production systems in the context of catchment-scale problems.

The paper provides an overview of APSIM (Agricultural Production Systems Simulator) and outlines its current state of development. APSIM is a modelling framework that can be variously configured to represent different agricultural systems. The particular features of APSIM that make it a useful tool in interdisciplinary research are discussed. These include a high degree of modularity which allows different biological, physical and environmental components (or modules) of the system under consideration to be "plugged-in" or "pulled-out". In addition, flexible management control allows complex, yet highly plausible management scenarios to be evaluated.

The paper considers the particular contribution that paddock-scale models can make to issues that manifest themselves as catchment-scale problems. The ability to concurrently assess the impacts of management strategies in terms that are relevant to both economic (eg. production in relation to inputs) and environmental (eg. deep drainage losses) assessment is seen as a critical contribution. This issue is explored by way of an example simulation in which APSIM is used to examine alternative decision rules for planting and fallowing in a wheat / sorghum rotation over the historical rainfall record for a site in northern NSW.

1. INTRODUCTION

Much of Australia's agricultural land faces serious problems of resource degradation that clearly operate on a broad-scale, catchment basis. The development of dryland salinity is one such problem that can only be fully comprehended at a watershed scale. Likewise, soil erosion and nutrient loss to surface or groundwaters are "catchment-scale" problems in agricultural systems as diverse as dryland grain/grazing farms in western NSW and high-rainfall sugarcane farms in the wet tropics of Qld. In the Liverpool Plains of northern NSW, changes in regional hydrology have caused rising water tables and salinisation. Lost production and decreasing land values have resulted. Over 195,000 ha of highly productive agricultural land (16% of the region) is estimated to be at risk over the next 10 years unless effective preventative action can be taken (Schroder et al. 1991, Broughton, 1994).

In this paper we argue the case for the contribution paddock-scale studies and models can make to the interpretation and resolution of catchment-scale problems. By way of illustration, the capabilities of APSIM (Agricultural Production Systems Simulator) are described. Application of APSIM is demonstrated by way of an example simulation, that examines crop production and deep drainage below the root zone in relation to cropping intensity in a wheat/sorghum cropping system.

2. SPATIAL AND TEMPORAL SCALES IN MODELLING

For the purposes of this paper, we define paddock-scale as unit of uniform soil that is managed in a uniform way. In some situations, physical paddocks may contain variation in soils or management that would not meet these criteria, but this can be conceptually dealt with as multiple "virtual" paddocks within the one physical paddock. We define catchment as a landscape unit delineated by some topographical (surface or groundwater) divide.

Individual catchments or basins qualify as systems in the natural world because they have emergent properties, which relate to the whole and are not merely the sum of the parts. As such, problems can be defined in terms of states of such emergent properties (rising water table salinity or water table contamination).

In terms of problem solving, (problem definition, solution design, and choice among alternative designs), catchments pose an interesting case. The system problem and evaluation of any solutions must be described in terms of the emergent properties. Yet because agricultural catchments are managed at the scale of the individual paddock, the design of management solutions involving some choice between alternative management options, also needs to focus at this scale. The reality is that paddock-scale management is associated with many different independent decision makers whose main purpose is not care of the catchment, (although they are not indifferent about this), but the conduct of a successful farm business. Changes in management that benefit the catchment will take place only if the changes benefit (or at least do not jeopardise) the financial performance of individual business units.

If this is a realistic analysis of the farming catchment, it poses some interesting challenges for scientific analysis and modelling aimed at alleviating problems. There is a tendency to assume that because the problem is a catchment problem, a catchment model is required to deal with it. It is often added, that this being the nature of the problem, then a paddock model is rather irrelevant. A catchment model appears useful for facilitating certain exploration of catchment function in relation to structure and climate, perhaps. But people are the key to better catchment management, and paddock models are proving to be of considerable value in aiding farmers to explore consequences of changes in crop and cropland management (McCown et al 1995a). Clearly we are at a challenging frontier in methodology that requires both catchment and paddock models, and innovative ways in which they may be interfaced.

At the **paddock-scale**, tools are needed to explore the bio-physical and economic impacts of land management choices open to farmers. The major attraction of a focus at this scale is that it is the level at which the majority of decisions are being made that ultimately determine the "health" of a catchment. Whether or not decisions are taken that have the potential to deliver a benefit at the catchment scale will depend to a large extent on the impact of that decision on the performance of the farm business, or on the policy environment that is put in place. The evaluation of both management and policy options requires well developed bio-physical / economic tools that are relevant at the paddock/farm scale. The downside of such a focus is that paddock scale models are not able to describe partial area runoff or to simulate lateral subsurface redistribution of water through the landscape. Neither are they currently capable of addressing the spatial distribution of crops, pasture, and trees that we might wish to evaluate in assessing alternative land use options (e.g. alley cropping). Paddock scale models cannot deal with the links between paddocks / farms and catchments and it's difficult to quantify the benefits of altered land management on farms to the overall status of the catchment. Working at the paddock scale alone, provides only limited information about which areas in a catchment will provide the best return to the overall catchment from some action that, for instance, reduces deep drainage.

At the **catchment scale**, tools are needed to explore the major processes that are operating, such as sources and sinks and major flows of water and salts. Such tools might be useful in identifying particular processes or regions of greater importance / sensitivity. Distributed parameter catchment scale models are available to simulate hydrological processes with spatially explicit descriptions of fluxes and storages at different time and space scales. Such models can incorporate the known spatial heterogeneity of soils, rainfall, and vegetation into predictions of catchment behaviour. Their major drawbacks are numerical complexity, the large number of input parameters required, and the uncertainty of finding a unique solution.

There is a general weakness in the ability of distributed parameter models to incorporate, and thus assess, the effect of changes in soil and crop management on the hydrology of the catchment. Whilst they may be able to generalise agronomic practice as a form of land use, they are unable to deal with aspects such as different crop rotations, fallow length, fertiliser and residue management etc. on catchment hydrology. This severely limits their applicability to the agronomic control of recharge, for example. With recharge control, and other applications, the solutions may still lie in the ways in which land is managed, tools which cannot incorporate agronomic management may only help in the definition of the problem, and add little to the solution.

The modelling of water quality as affected by dryland salinity requires the modelling of groundwater flow at the scale of the catchment. However, many such modelling efforts require *a priori* specification of recharge and inputs of solute expected under changing soil or crop management or climate. This requirement can be usefully met by one-dimensional soil water and solute models and is a good example of the value in combining models of processes at different scales.

While we have focused on the distinction between paddock and catchment scale, there will be instances where modelling at the farm-scale is appropriate and necessary. In this we include the bio-physical performance of multiple paddocks, perhaps as some summarised form of separate paddock modelling activity, together with the capital, cash-flow, labour and other socio-cultural factors that impact on the performance of the farm business.

3. APSIM

APSIM (Agricultural Production Systems Simulator) in its most distilled form (Figure 1), is a software environment which consists of models of elements of a system (referred to as modules) and a communications systems (engine and module interfaces) that allows modules to share information (McCown et al 1995b).

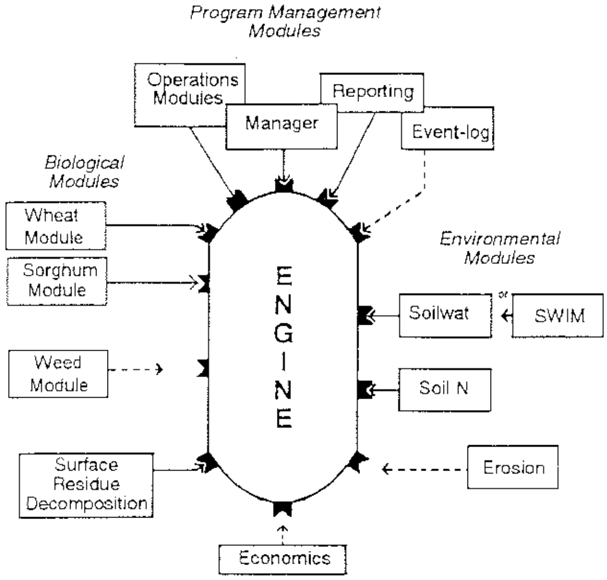


Figure 1. Diagrammatic representation of APSIM modules and communications system.

While the software protocols used in APSIM are general, development to date has focused on agricultural systems and in particular crop, soil and management elements. Pasture and to a lessor extent, grazing elements have received only minor attention to date.

APSIM reflects a conceptual view of agricultural systems that includes :

- the notion that the soil is the central continuing element, crops, pastures and animals come and go, finding the soil in one state and leaving it in another state.

- the notion that not all potential elements of a system are always important or relevant to a particular issue at hand. Hence, modules need to be "plugged-in" and "pulled-out" without negatively affecting the software integrity. Related to this is the notion that alternative approaches will exist to the simulation of a particular component. The ability to easily replace one module with an alternative, promotes a healthy exploration of modelling strategies.

- the notion that the temporal resolution needed to adequately interpret the behaviour of some part of the system will vary with process under consideration. Hence, while a great many modules operate on a daily timestep, variation in time step is possible, for instance down to one hour for a water balance module (SWIM, Ross 1990) redistributing water during a rainfall event to more than 3 months for a crop module returning roots to the soil organic matter pools.

3.1 Modules

Modules currently available or under development for APSIM are summarised in Table 1.

Module Group	Module Name	Description
Crops	NWHEAT	Wheat crop model
	SORGHUM	Sorghum crop model
	OZCOT#	Cotton crop model
	SUNFLOWER	Sunflower crop model
	MAIZE	Maize crop model
	BARLEY	Barley crop model
	COWPEA	Cowpea crop model
	PEANUT	Peanut crop model
	SUGARCANE	Sugarcane crop model
Pasture	Stylo	Annual Stylosanthes pasture model
	GRASP	Tropical and subtropical native grassland (McKeon et al 1990)
Soil	SOILWAT	"Tipping bucket" style water balance
	SOILN	Comprehensive soil N balance
	SWIMv2*	Water and solute flux based on Richard's eq. and C-D Eq.
Soil Surface	RESIDUE	Decomposition of crop and pasture residues at the soil surface
	EROSION	Soil and nutrient removal associated with erosion through runoff

\# By arrangement with CSIRO Plant Industry
* By arrangement with CSIRO Soils

Table 1. Modules currently available or under development for APSIM.

In addition to the modules currently available, work is currently underway to build modules for the chickpea crop, lucerne, and perennial grass pastures and <u>Eucalyptus grandis</u> plantations (V. Snow, pers comm.)

3.2 Manager and system control

At the outset we acknowledged that the ways in which agricultural systems were managed were highly variable and complex and it was not going to be possible to explicitly allow for all the possible permutations and combinations of management tactics and strategies that were possible. This problem was resolved via the construction of a "Manager" module for APSIM which allows complex conditional rules to be established. These rules allow actions to be initiated either unconditionally, or more normally, when a set of conditions are met. For example, within APSIM, the following manager module inputs :

```
if  day > 120     and
    day < 240     and
    sw_dep() > 640  and
    sw(2) > 0.40  and
    rain[10] > 25 then
 fertiliz apply amount = 60 (), depth = 50 (), type = urea_n
 cw sow 90 30 hartog
endif
```

translates to the following decision rule:

"Plant a wheat crop (cultivar hartog) and fertilise it with 60 kg N ha^{-1} as Urea, in a planting window between 1st May and 27th August, but only after a cumulative planting rain of 25 mm has fallen over a 10 day period and only if the soil profile is more than 50% recharged with water. "

In addition to the MANAGER module, other modules exist for system control, including INPUT, REPORT, OPERATIONS, IRRIGATE, FERTILISE, EVENT_LOG, ACCUMULATOR and ARBITRATOR. The ARBITRATOR can be used to simulate more than one plant species competing for light, water or nitrogen (eg intercrops, crop - pasture interactions, crop-weed interactions).

4. AN EXAMPLE : CROPPING STRATEGIES, PRODUCTION and DEEP DRAINAGE

Crop production on the clay soils of the north-east cereal belt relies on a combination of in-season rainfall and moisture storage over fallows of varying duration. Long fallows, whilst generally thought to reduce the risks of subsequent crop production, are known to be inefficient strategies of storing scarce rainfall for crop production (Freebairn and Hitchener 1983). Runoff, evaporative losses and deep drainage losses all contribute to varying degrees to low efficiencies of rainfall storage in the soil during fallows. A range of intrinsic soil properties, soil and residue management factors will interact with rainfall patterns and cropping strategies to determine the relative importance of each of these terms in the water balance. In this example, we examine how a crop-soil-management simulator can be used at the paddock-scale to provide information on the implications on the likely productivities and deep drainage losses of alternative crop management strategies.

The simulations that we report use preliminary input data only. They are presented only to provide an example application of the crop-soil-management simulator and to illustrate the periodicity of drainage below the root zone. Work is currently underway to ensure the various crop and soil modules provide valid representation of crop and soil processes in the Liverpool Plains region.

4.1 Methods

A notional clay soil was parameterised with properties outlined in Appendix A. Weather data were for the town of Moree in northern NSW. Daily rainfall was as processed by RAINMAN (Clarkson and Owens 1991) to check for errors and fill any gaps in the record extending from 1880 to 1994. Temperatures and radiation data were estimated using a combination of local records and the procedures outlined by Meinke at al 1994.

Two management strategies were simulated. Planting rules for each strategy are shown in Appendix A. In the FIXED strategy, a wheat - long fallow - sorghum - long fallow strategy was simulated, based on decision rules that aimed to grow a wheat crop followed by a long fallow (i.e., approx. 12 mths) followed by a sorghum crop and a long fallow. The rotation would then be repeated. If the planting criteria were not met for a particular crop in a particular year, an attempt to plant that "missed" crop in the next year would be made and the rotation adjusted accordingly. The net effect of these rules was that the fallow length was never less than 12 mths and could be longer if planting opportunities did not occur. In the FLEXIBLE strategy, a wheat-sorghum rotation was simulated, with planting taking place within defined "windows" whenever soil water status exceeded 50 % of the fully wet state and planting rains were received (Appendix A). The effect of this rule was a much higher cropping intensity, with no forced long fallows.

The wheat cultivar simulated was Hartog and sorghum was DeKalb DK55. Fertiliser (60 kg N ha^{-1} as Urea) was applied each time a crop was planted and crop residues were retained, and subjected to a simulated tillage operation which incorporated 60% of the residue into the 0 to 15 cm layer. The combination of fertiliser N and residue retention was sufficient to maintain soil fertility at non-limiting levels throughout the simulation.

4.2 Simulations

4.2.1 Cropping Intensity

The enforced long-fallow rules used in the fixed cropping strategy resulted in a cropping intensity only 70% of that achieved in the flexible strategy (Table 2).

	FIXED	FLEXIBLE
Number of wheat crops	36	60
Number of sorghum crops	34	40
TOTAL	70	100

Table 2. The cropping intensity simulated for two rotational strategies (Appendix A) over 115 years at Moree in northern NSW.

4.2.2 Crop Production

Simulated wheat and sorghum yields ranged from 0 to 7000 and 0 to 5500 kg ha^{-1} respectively (Figure 2). Variability in simulated yields was high with coefficients of variation in the order of 80 - 90 % for wheat and 95 -

100 % for sorghum. An historically dry period in the 1930's and 1940's limited both sowing opportunities and crop yields. This dry period is evident when the cumulative deviation from the long-term mean rainfall is calculated over the 115 year rainfall record (Figure 3).

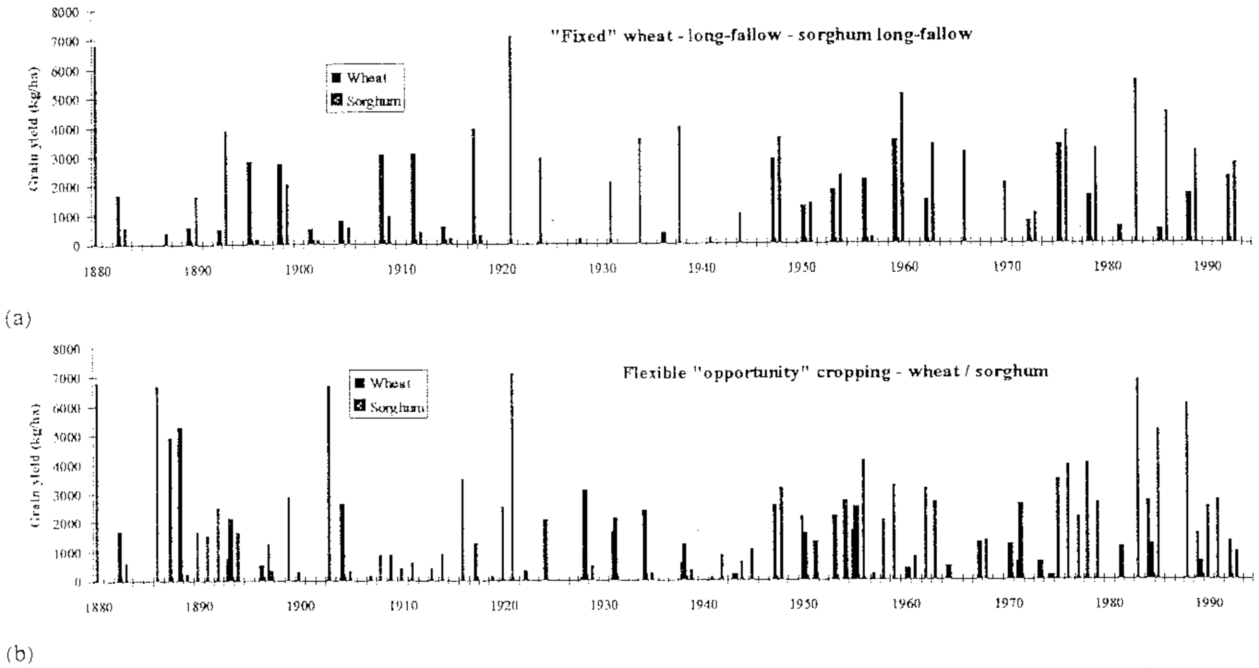


Figure 2. Simulated sequence of grain yields (kg/ha) at Moree in northern NSW over the 1880 to 1994 period.
(a) Fixed wheat / long-fallow / sorghum / long-fallow rotation.
(b) Flexible wheat / sorghum rotation with sowing based on soil water storage.

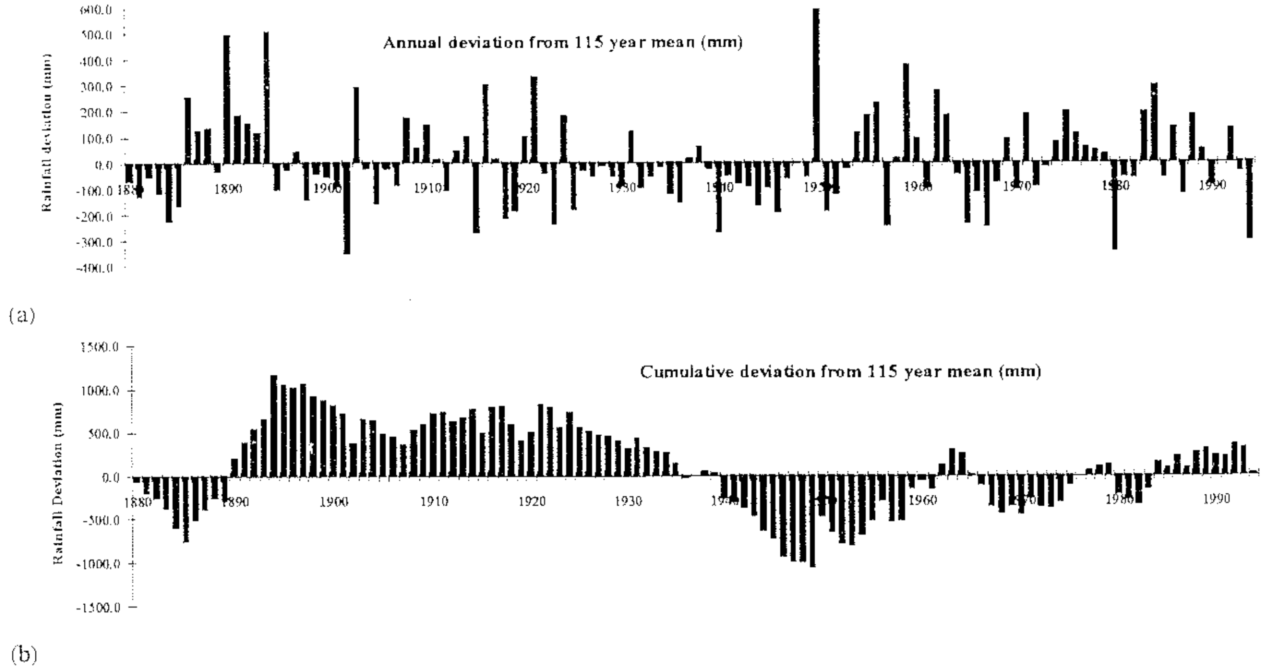
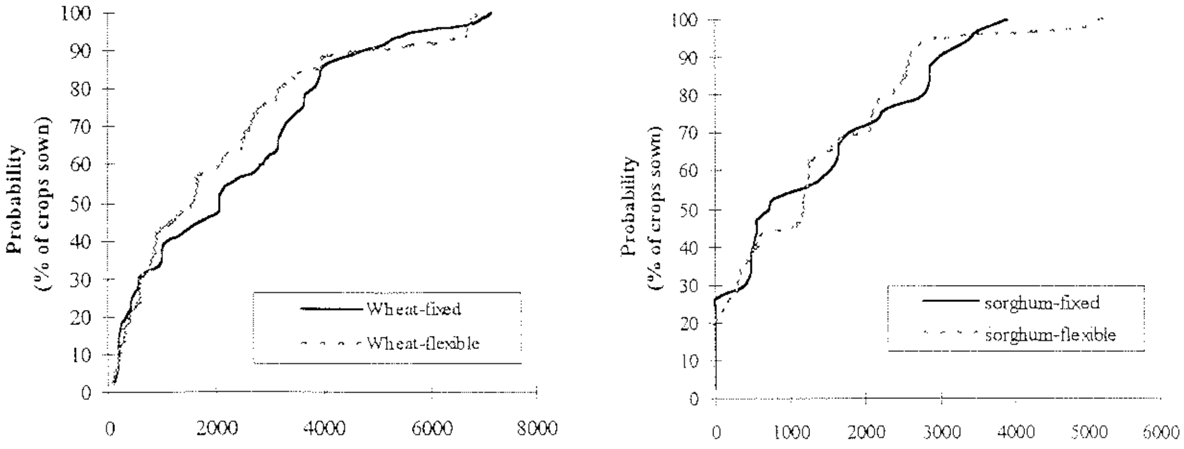


Figure 3. Deviation in annual rainfall at Moree from 115 year mean. (a) Annual ; (b) Cumulative.



(a) (b)

Figure 4. Cumulative probability of producing less than the specified grain yield (kg/ha) simulated for fixed and flexible wheat / sorghum rotations at Moree in northern NSW over the 1880 to 1994 period. (a) Wheat ; (b) Sorghum

While crop yields were generally lower under the FLEXIBLE strategy for both wheat and sorghum (Figure 4), the higher cropping intensity meant that total production or annual average production over the 115 year period was estimated at being 47% higher for wheat and 21 % higher for sorghum (Table 3).

Average production	FIXED	FLEXIBLE
Wheat (kg/ha/year)	736	1110
Sorghum (kg/ha/year)	380	461
Median wheat yield (kg/ha)	2090	1619
Median sorghum yield (kg/ha)	750	1191

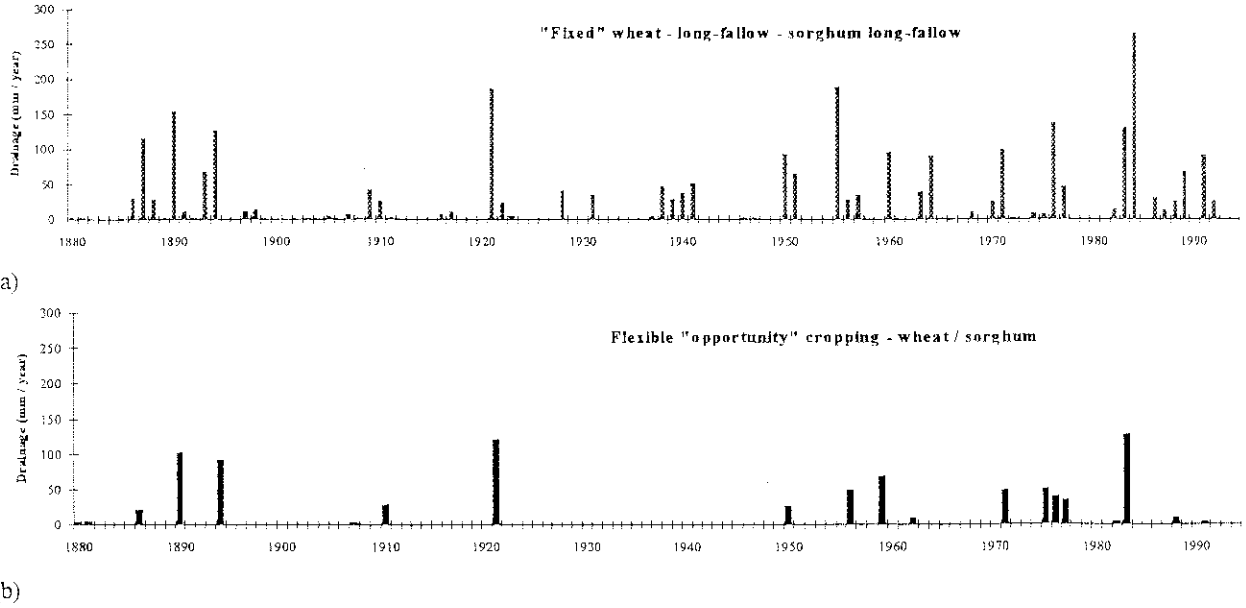
Table 3. The effects of alternative cropping strategies (Appendix A) on simulated crop production over 115 years at Moree in northern NSW.

4.2.3 Drainage below root zone

The lower intensity of cropping in the FIXED strategy resulted in less water use by vegetation and as a consequence, both runoff and drainage below the root zone were simulated to be greater than in the more intensively cropped FLEXIBLE strategy (Table 4, Figure 5).

	FIXED	FLEXIBLE
Average rainfall (mm/year)	577	577
Average runoff (mm/year)	55	39
Average drainage (mm/year)	24	7

Table 4. The effects of alternative cropping strategies (Appendix A) on the simulated water balance over 115 years at Moree in northern NSW.



(a)

(b)

Figure 5. Simulated sequence of annual drainage amounts (mm) at Moree in northern NSW over the 1880 to 1994 period.
(a) Fixed wheat / long-fallow / sorghum / long-fallow rotation.
(b) Flexible wheat / sorghum rotation with sowing occurring based on soil water storage.

5. CONCLUSIONS

In many situations, catchment-scale problems arise because of the net effect of a great many paddock- scale decisions, whether they be to clear trees, cultivate soils, fallow land, grow shallow rooted annual pastures, burn stubble, apply fertilisers etc. Our contention is that these aspects cannot, at the moment, be dealt with adequately in catchment scale models. They are best dealt with in a paddock scale framework where the complexities of soil and crop management can be included, where economic analyses can be incorporated, and where results can be well tested.

APSIM (Agricultural Production Systems Simulator) with its array of component modules, is considered to have a role in the study of both on-site and off-site issues of resource degradation. One of the strengths of APSIM is its ability to address complex, highly conditional management strategies. It is in the area of management effects on production, profit and the small-scale water balance that these paddock-scale approaches make their major contribution. The example presented demonstrates how a change in the decision rule that a farmer may invoke to determine rotational strategies can have major impact on both total production, the riskiness of production and the drainage and runoff terms in the water balance.

A new study is now underway with LWRRDC support to evaluate and further develop our capability to simulate the effects of both crop and pasture elements of the farming systems of two national focus catchments, namely the Liverpool Plains in northern NSW and Loddon/Campapse in Vic. While various elements of the models used have been well tested in other locations, further model testing and additional effort in model parameterisation is needed in these areas.. As stated earlier, the results presented in this paper are of a preliminary nature.

What is also clear is that paddock-scale models alone cannot address all the issues that are relevant to catchment-scale problems. Other approaches are needed to deal with the above-ground and below-ground flows of water and salts across the landscape and the relative importance of different regions or hydrogeological units to a catchment-scale hydrological problem. The scientific and sometimes institutional challenge is for approaches at both scales to effectively engage, so that insight gained at either scale adds value to the work done at the alternative scale. This paper has focused on bio-physical issues, but a similar challenge exists in interfacing insight of a bio-physical nature, with the very real economic and social dimensions of resource degradation.

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Appendix A. Soil properties and management rules used in the example simulation.

Soil Water Profile Properties

Depth-mm	LL15	DUL	SAT	BD
0.- 150.	0.310	0.490	0.550	1.030
150.- 300.	0.310	0.490	0.550	1.060
300.- 600.	0.310	0.490	0.550	1.060
600.- 900.	0.350	0.490	0.550	1.080
900.- 1200.	0.390	0.480	0.530	1.110
1200.- 1500.	0.420	0.480	0.530	1.140
Totals	534.0	729.0	813.0	

Cona	U	Salb	Dif_Con	Dif_Slope
3.50	6.00	0.13	88.00	35.00

Cn2	Cn_Red	Cn_Cov	H_Eff_Depth
76.00	20.00	80.00	450.00

Soil Nitrogen

Layer	pH	OC	NO3	NH4
1	7.50	2.19	10.82	2.32
2	8.00	1.98	6.68	1.59
3	8.20	1.82	8.59	1.59
4	8.50	1.47	4.21	1.62
5	8.60	1.14	5.99	1.66
6	8.80	0.85	17.10	1.71
Totals			53.39	10.49

LL15 = Lower limit of plant extractable water (g cm^{-3})
DUL = Drained upper limit of soil water (g cm^{-3})
SAT = Saturated soil water content (g cm^{-3})
BD = Bulk density (g cm^{-3})
Cona, U = Parameters of the soil evaporation model
Salb = Soil albedo
Dif_Con, Dif_Slope = Parameters of the unsaturated soil water movement model.
Cn2 = Runoff Curve Number
Cn_Red, Cn_Cov = Trash effect on Curve Number
H_Eff_Depth = Soil depth over which antecedent water influences runoff.
OC = Soil organic carbon %
NO3, NH4 = Initial mineral nitrogen contents (ppm)

Management Strategies

GENERAL

Wheat Sowing Window	Days 120 to 240
Sorghum Sowing Window	Days 300 to 364
Planting Rains	25 mm over a 10 day period
Soil water criterion for planting	> 0.40 Vol. soil water in 15-30 cm
Wheat sowing rate	90 plants m^{-2}
Sorghum sowing rate	16 plants m^{-2}
Wheat cultivar	Hartog
Sorghum cultivar	DeKalb DK55
Fertiliser Rate	60 kg N ha^{-1} as Urea at sowing
Residue Management	Retain 20 % of stubble on surface

FIXED
Minimum 12 month fallow between crops.

FLEXIBLE
No minimum fallow length
Plant when soil water > 640 mm (i.e. plant available water > 54% of total)